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Extreme floods in central Europe over the past 500 years: Role of cyclone pathway "Zugstrasse Vb"

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[1] Anthropogenically induced climate change has been hypothesized to add to the risk of extreme river floods because a warmer atmosphere can carry more water. In the case of the central European rivers Elbe and Oder, another possibility that has been considered is a more frequent occurrence of a weather situation of the type "Zugstrasse Vb," where a low-pressure system travels from the Adriatic region northeastward, carrying moist air and bringing orographic rainfall in the mountainous catchment areas (Erzgebirge, Sudeten, and Beskids). Analysis of long, homogeneous records of past floods allows us to test such ideas. M. Mudelsee and co-workers recently presented flood records for the middle parts of the Elbe and Oder, which go continuously back to A.D. 1021 and A.D. 1269, respectively. Here we review the reconstruction and assess the data quality of the records, which are based on combining documentary data from the interval up to 1850 and measurements thereafter, finding both the Elbe and Oder records to provide reliable information on heavy floods at least since A.D. 1500. We explain that the statistical method of kernel occurrence rate estimation can overcome deficiencies of techniques previously used to investigate trends in the occurrence of climatic extremes, because it (1) allows nonmonotonic trends, (2) imposes no parametric restrictions, and (3) provides confidence bands, which are essential for evaluating whether observed trends are real or came by chance into the data. We further give a hypothesis test that can be used to evaluate monotonic trends. On the basis of these data and methods, we find for both the Elbe and Oder rivers (1) significant downward trends in winter flood risk during the twentieth century, (2) no significant trends in summer flood risk in the twentieth century, and (3) significant variations in flood risk during past centuries, with notable differences between the Elbe and Oder. The observed trends are shown to be both robust against data uncertainties and only slightly sensitive to land use changes or river engineering, lending support for climatic influences on flood occurrence rate. In the case of winter floods, regional warming during the twentieth century has likely reduced winter flood risk via a reduced rate of strong river freezing (breaking ice at the end of winter may function as a water barrier and enhance a high water stage severely). In the case of summer floods, correlation analysis shows a significant, but weak, relation between flood occurrence and meridional airflow, compatible with a "Zugstrasse Vb" weather situation. The weakness of this relation, together with the uncertainty about whether this weather situation became more frequent, explains the absence of trends in summer flood risk for the Elbe and Oder in the twentieth century. We finally draw conclusions about flood disaster management and modeling of flood occurrence under a changed climate. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1620 Global Change: Climate dynamics (3309); 1655 Global Change: Water cycles (1836); 1821 Hydrology: Floods; *KEYWORDS:* climate change, extreme events, flood risk

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1. Introduction

[2] Extreme river floods have had devastating effects in central Europe in recent years. For example, the Elbe flood in August 2002 caused 36 deaths and over 15 billion USD damages [*Grünewald*, 2003; *Mueller*, 2003; *Sercl and Stehlik*, 2003], and the Oder flood in July 1997 caused 114 deaths and around 5 billion USD damages [*Grünewald et al.*, 1998; *Grünewald*, 2003]. Although this type of natural hazard has been recorded over the past several centuries [*Brázdil et al.*, 1999; *Pfister*, 1999; *Pfister et al.*, 1999; *Glaser*, 2001], concern is expressed in the Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [*Houghton et al.*, 2001] that current anthropogenic changes in atmospheric composition will add to this risk. The concern is based on regional climate model studies presented by *Giorgi et al.* [2001], who found that under various greenhouse gas emission scenarios, regional and seasonal precipitation is likely to increase. The physics behind the increase in occurrence of extreme precipitation is governed by the Clausius-Clapeyron equation [*Allen and Ingram*, 2002], which describes how warmer air can carry higher contents of water vapor. Recent experiments with regional models for the European area employed a higher spatial resolution and confirmed this finding, suggesting an increased rate of occurrence of extreme precipitation in Europe during both winter [*Palmer and Räisänen*, 2002] and summer [*Christensen and Christensen*, 2003].

[3] However, the variable modeled in these studies is precipitation, not water stage or runoff in a river. What portion from the precipitation actually arrives in a river may depend on several time-dependent factors. One factor is land use changes, for example, deforestation [*Bork et al.*, 1998] and agricultural intensification [*van der Ploeg and Schweigert*, 2001], which reduce the water retention capability of the soil. Another factor is river engineering, that is, construction of reservoirs and designation of polder areas to be used for flood management, and also building of dams or length reductions. The regional effects of both on the flood risk are debated [*Grünewald et al.*, 1998]. (In this paper, we use the expressions ''risk'' and ''occurrence rate'' synonymously to refer to the probability of an event within a time period.) *Middelkoop et al.* [2001] modeled the runoff of the river Rhine, incorporating climate variables (precipitation, temperature, etc.) predicted by Global Climate Models (GCMs) for a 2 × CO_2 situation into different types of hydrological models with realistic land use schemes. They found higher winter runoff as a result of intensified snowmelt and increased winter precipitation and lower summer runoff due to the reduced winter snow storage and an increase of evapotranspiration. However, these authors also note discrepancies between results from different hydrological models and consider that the low spatial resolution of the GCM output makes it [*Middelkoop et al.*, 2001, p. 119] ''difficult to achieve reliable estimates of peak flows under changed climate conditions.'' Note also that the hydrological regime of the Rhine is influenced by Alpine climate, not low-range mountainous climate (earlier snowmelt) as is the case for many other European rivers.

[4] Data analyses fail to reveal unambiguous trends in flood risk in European rivers over the past decades. *Caspary and Bárdossy* [1995] analyzed yearly maximum runoff time series from the river Enz (SW Germany) at two stations from 1930 to 1994 by making a polynomial regression and fitting a Gumbel extreme value distribution to various time intervals. They detected an increase in flood risk toward the present attributed to an increase in occurrence of zonal westerly circulation systems. *Caspary* [1995] obtained similar results from yearly maximum runoff time series from the upper Danube station Beuron from 1926 to 1995. Since no tests of model suitability were performed in these papers and no error bars were provided, it is difficult to assess the significance of these increases. *Black* [1995] analyzed annual mean runoff time series from 15 Scottish rivers from ~1950 to 1994 and found maxima to occur predominantly after 1989 and in rivers with catchments exposed to the west. He attributed this to climatic influences, although 14 rivers from England and Wales also analyzed by him did not show such behavior. *Bendix* [1997] took annual maximum runoff series from the river Rhine at station Cologne from 1821 to 1995 and station Bonn from 1900 to 1995 to perform linear regression and found significant upward trends, which he interpreted to reflect an increase in flood risk. *Disse and Engel* [2001] analyzed monthly mean runoff time series (March, April, and May) from the river Rhine at station Cologne from 1931 to 1960 and 1961 to 1998 using linear regressions and found, although there might be an increase in mean runoff from the older to the younger interval, slopes to be rather small and not of consistent sign among the three months and between the two intervals. They concluded that [*Disse and Engel*, 2001, p. 271] ''a strong relationship between recent climate change observations and the occurrence of flood levels cannot be proven.'' *Robson* [2002] analyzed daily runoff time series from 30 river stations across the United Kingdom from ~1800 to 2000 using various techniques (linear regression, nonparametric tests, and a peak-over-threshold approach) and concluded that although [*Robson*, 2002, p. 1327] ''trends towards more protracted high flows over the last 30–50 years'' appeared significant, those trends can be within climatic variability. Furthermore, ''no statistical evidence of a long-term trend in flooding over the last 80–120 years'' was found. *Sturm et al.* [2001] analyzed monthly maximum runoff series (midnineteenth century to present) and floods documented in historical records (1500–1799) of the European rivers Elbe, Main, Rhine, Saale, and Weser using a kernel technique (running 31-year windows). Although trend patterns among those rivers were more coherent for winter flood occurrence than for other seasons, *Sturm et al.* [2001] could not demonstrate the significance of those trends in recent decades. *Jacobeit et al.* [2003] analyzed the same flood data and their relation to sea level pressure (SLP) fields and confirmed the relevance

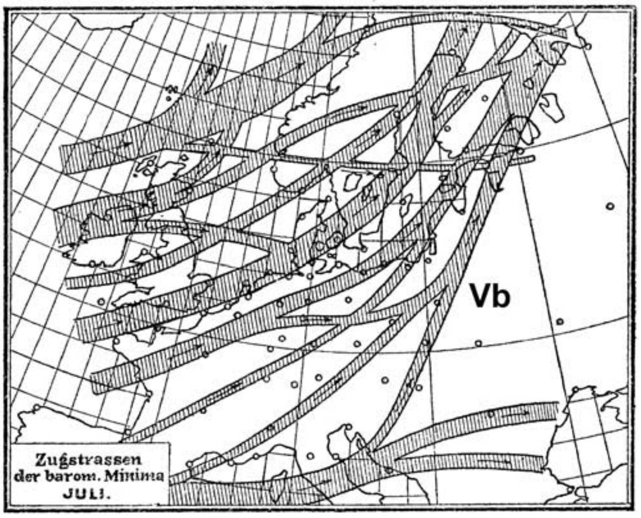

Figure 1. Late nineteenth century view of cyclonic atmospheric pressure systems or barometric minima coming from the west and traveling on a few preferred pathways ("Zugstrassen") across Europe, here shown for July. Lows moving on the "Zugstrasse Vb" take up warm, moist air over the Adriatic region and move in a northeast direction. This may lead to orographic rainfall in the catchment areas of the Elbe and Oder (Figure 2) and cause summer floods, as was suggested by, among others, *Hellmann and von Elsner* [1911]. (Map modified from *van Bebber* [1898].)

of the westerly zonal circulation type for the occurrence of winter floods [*Caspary and Bárdossy*, 1995]. However, *Jacobeit et al.* [2003] also showed that in former centuries other modes of atmospheric circulation were important, such as a situation with an Atlantic low and a Russian high-pressure center. *Sheffer et al.* [2003] analyzed sedimentary deposits of floods in the small French river Ardèche during the late Holocene (past ~2000 years), took a peak-over-threshold approach and found the return period of these events lower than return periods that were estimated using recent precipitation data and the assumption of a "parallelism between the upper tails of the flood volume distribution and the rainfall volume distribution" (paragraph 35). Their conclusion of a nonstationarity, with the indication that "the LIA [Little Ice Age] was a more active flood period than the previous and later periods" (paragraph 42) seems premature, given the various sources of statistical (the number of floods at three sites is as low as 30) and systematic errors inherent to paleoflood analyses and the possible violation of the quoted assumption.

[5] At the end of the nineteenth century, W. J. van Bebber developed the hypothesis that low-pressure systems moving from the northern Atlantic to the European area prefer certain pathways ("Zugbahn" or "Zugstrasse"). In an analysis [*van Bebber*, 1898] for the period 1876–1889 (5114 days), he found 1440 days (28%) where at least one of six defined pathways was occupied. Only the "Zugstrasse Vb" (Figure 1) seems to have survived as a useful explanatory tool, primarily in connection with flood occurrence in the central European region. In a Vb situation, a cyclone transports warm and moist air from the Adriatic region and moves in a northeast direction. Upon reaching low mountain ranges (Bohemian Massif, Erzgebirge, Sudeten, and Beskids), the air is orographically lifted over an extended area (Figure 2). Producing large amounts of rainfall in a Vb situation requires a combination of (1) meridional and cyclonic airflow, (2) high water vapor content, (3) low convective lability, preventing cell formation, and (4) prolonged (~0.5 days and more) flow against orography, relating to a slow movement of the long wave. The long or Rossby wave thereby defines the "Großwetterlage" (general weather situation) in Europe (F.-W. Gerstengarbe et al., Katalog der Großwetterlagen Europas (1881–1998) nach Paul Hess und Helmuth Brezowsky, 5th ed., online document, http://www.pik-potsdam.de/~uwerner/gwl/welcome.htm, 1999). The Großwetterlage "Troglage Mitteleuropa" (TrM) (trough situation in central Europe) contains the Vb situation as one element. *Fricke and Kaminski* [2002] suggest that an increase in the occurrence of extreme rainfall at the station Hohenpeienberg (northern Alps) during the past 120 years is related to an increase in the occurrence of the Großwetterlage TrM.

[6] This paper focuses on improving data quality and enhancing data analysis techniques to bring models and observations of extreme floods in central Europe closer together. In a recent paper [*Mudelsee et al.*, 2003] (hereinafter referred to as M03), we have presented flood records for the rivers Elbe and Oder, which have monthly resolution and go continuously back to A.D. 1021 and A.D. 1269, respectively. Here we review data reconstruction in detail

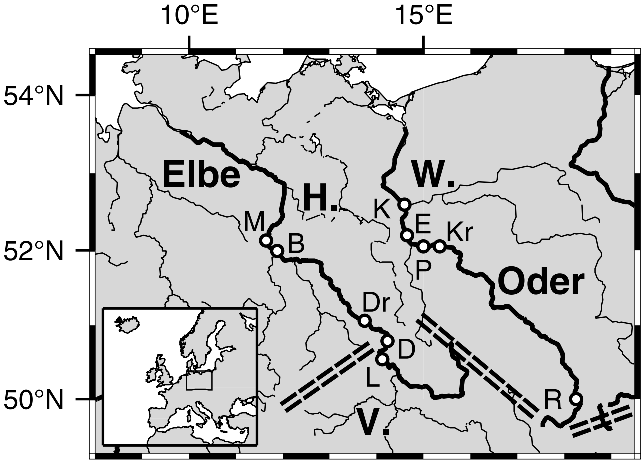

Figure 2. Hydrographic map showing major rivers in central Europe (see inset) under a low-range mountainous climate: Elbe and Oder, whose mouths enter the North Sea and Baltic Sea, respectively. Flood analyses focus on the middle Elbe (between Litoměřice (L) and Magdeburg (M)) and middle Oder (between Racibórz (R) and before Kostrzyn (K)) to prohibit the influence of tributaries Havel (H.) and Warta (W.). Schematically drawn (double-dashed lines) are, from west to east, mountains Erzgebirge, Sudeten, and Beskids. Another orographically relevant feature is the Bohemian Massif, located south of tributary Vltava (V.). Water stage and runoff time series from the following stations are analyzed: Děčín (D), Dresden (Dr), Barby (B), Krosno (formerly Krossen) (Kr), Połęcko (P), and Eisenhüttenstadt (formerly Fürstenberg) (E).

and assess quality aspects such as homogeneity (section 2). We further advocate (section 3) kernel occurrence rate estimation as a method that can overcome limitations of the techniques mentioned above. For criticism of current statistical techniques employed in climatology to analyze extremes, see *Intergovernmental Panel on Climate Change* [2002]. In particular, given the rarity of extreme events and natural climate variability, it is important to assess the significance of a trend in flood occurrence. Kernel occurrence rate estimation advantageously permits detection of nonlinear and nonmonotonic trends. In that manner, time intervals of highs and lows in flood risk may be related to climatic periods, providing climate-hydrology models with indications of relevant forcing variables. Finally, we analyze the point-wise biserial correlation between flood occurrence in the rivers and SLP fields to study the role of large-scale atmospheric circulation patterns over the past 500 years, in particular the Zugstrasse Vb. In the discussion of results (section 4) we weight the influences of climatic, land use, and river-engineering changes on flood occurrence. The conclusions (section 5) of our data analyses are aimed at modelers of hydrological extremes under climate changes.

2. Data

[7] The rivers Elbe and Oder drain basins that are under a continental, low mountainous climate (Figure 2). Floods in hydrological summer (May to October) are caused by heavy rainfall, and in the winter (November to April) also by thawing snow [*Fischer*, 1907; *Grünewald et al.*, 1998]. Breaking river ice may function as a barrier, enhancing winter floods severely [*Grünewald et al.*, 1998]. We selected the middle Elbe (between Litoměřice and Magdeburg) and middle Oder (between Racibórz and before Kostrzyn) because of availability of long measured runoff records and abundant documentary information on past flood events. This choice also prohibited influences in the flood records from other regional climates via the tributaries Havel and Warta. Catchment area sizes are ~95,000 km^2 (middle Elbe) and ~54,000 km^2 (middle Oder), allowing for results representative at a regional scale.

2.1. Elbe Floods

2.1.1. Historical Period

[8] For collecting information of Elbe floods in the historical period, M03 relied mainly on C. Weikinn's sources on hydrographic events in Europe [*Weikinn*, 1958, 1960, 1961, 1963, 2000, 2002]. Of the 23,160 entries, coverage is highest for Germany and neighboring countries. The sources cover the interval from A.D. 0 to 1850. One major problem when estimating occurrence rates on the basis of documentary data is inhomogeneity. Fewer documents about floods from an early period, compared with following periods, have lasted until they became included in secondary compilations such as C. Weikinn's. Also, the perception of floods was likely different in early times [*Glaser*, 2001]. These effects lead to missed events and result in underestimated flood occurrence rates. M03 therefore began their observation interval of Elbe floods at A.D. 1021, following a year with a reported flood of an unknown season and after which reports seem to become more abundant. This choice is somewhat arbitrary but not of high relevance since the interpretation of flood occurrence rates (section 4.1) focuses on the time since A.D. 1500.

[9] To construct a chronology that is regionally representative (middle Elbe), local events were excluded in M03 by imposing the following requirements: (1) At least two roughly simultaneous floods at different locations on the river were recorded. The most abundant information on floods in the historical period came from the stations Litoměřice, Pillnitz, Dresden, Meißen, Torgau, Wittenberg, Aken, and Magdeburg. (2) Roughly simultaneous floods in tributaries were recorded. The most important in this respect were the rivers Vltava, Mulde, and Saale. (3) Favorable meteorological conditions prior to a flood were noted. In the case of winter floods, M03 identified two main types in such recordings: first, a large snow cover followed by thawing and, second, a strong river freezing with a subsequent breakup owing to warming. Summer floods were found to be related to two types of rainfall. The first is prolonged (over weeks, even months) and not necessarily of high intensity. It also acts via saturation of the soil. The second type is cloudburst-like (maximum a few days), occurring on a larger than local scale. M03 achieved temporal differentiation by assessing whether two flood events were separated by an amount of time large enough (several weeks) to exclude the possibility that the second reported event was merely a product of the first. Information relating to whether a report used the old or new calendar (reform in A.D. 1582) was usually provided by C. Weikinn.

[10] The type of flood information in the C. Weikinn sources varies. The length of high water stages can often be inferred, casualties and damages are frequently reported, and comparisons with earlier floods are occasionally made. However, such records are inevitably subject to some degree of perceptional bias [*Glaser*, 2001]. The number of different sources can be helpful to assess the magnitude of a flood, although the number of independent sources may be considerably lower. Stage values are also given in some entries, notably from the stone bridge in Dresden, later named "Augustusbrücke," since ~1500. The most important sources of historical flood stages we consulted are *Pötzsch* [1784, 1786, 1800], *Schäfer* [1848], and *Königliche Elbstrombauverwaltung* [1898]. Runoff (volume per time interval), a more helpful quantity than stage for measuring the magnitude of a flood, was only measured at some occasions in the nineteenth century [*Königliche Elbstrombauverwaltung*, 1898]. A time dependence in the stage-runoff relation (section 2.1.2) can therefore introduce error in determining the flood magnitude. All of these uncertainties limit the number of magnitude classes that can be reliably analyzed. In a pioneering study of floods in the sixteenth century, *Brázdil et al.* [1999] developed an impact-related magnitude scheme, which was adapted by M03 as follows: Class 1 includes minor flood, with a brief period of overflow; no casualties reported, only minor damages caused; likely not a supraregional phenomenon; water stage (Dresden) between 600 and 690 cm. Class 2 includes strong flood, longer duration; reported casualties or large damages (e.g., to river buildings); water stage (Dresden) between 690 and 770 cm. Class 3 includes exceptionally strong flood, longer duration; large numbers of casualties, heavy damages; likely a supraregional event; water stage (Dresden) above 770 cm.

[11] A number of flood events (34) remained doubtful after the evaluation: Such events are reported by one non-contemporaneous source only; no indirect supportive information exists, such as, for example, floods in tributaries or a favorable meteorological situation. These events were not used for statistical analysis.

2.1.1.1. Exceptionally Strong Floods

[12] Eighteen class 3 events were found for the historical period. For the July 1315 and summer 1316 events, reports about both events come mainly from Bohemia, also noting strong rainfall events. Because one source lists both events, misdating seems unlikely. The July 1342 event was probably one of the heaviest floods of the millennium, affecting large areas in central Europe [*Tetzlaff et al.*, 2002]. For the June–July 1434 event, only scarce information is provided, however, with a somewhat stronger wording than for other events. The August 1501 event was well noticed; the water stage at Dresden was given as 10 Dresdener Ellen (866 cm) by *Schäfer* [1848]. The same stage was reported for January–March 1566, a winter flood enhanced by breaking ice. The January–February 1570 event was as before, with reports from many locations on the middle Elbe. Also, the floods in February–March 1595, March 1598, and February–March 1599 were “ice floods.” The January–March 1651 event was caused by breaking ice and thawing in January. Although maximum flood stage at Dresden is reported as 753 cm, we sorted this event into class 3 because of its long duration. The February 1655 event was again an ice flood, with a water stage at Dresden of 897 cm. For the June–July 1675 event, many reports exist about this summer flood (water stage 810 cm) without description of rainfall leading to it. A prolonged, wet summer led to the June–July 1698 event (786 cm stage). The February–March 1784 event was an ice flood (859 cm stage), described by many sources and inspiring the research of *Pötzsch* [1784, 1786, 1800]. The February 1799 event was an ice flood not as strong (829 cm stage) as the preceding one. The March 1830 event was an ice flood not as strong (798 cm stage) as the preceding two. The March–April 1845 event was an ice flood, at some locations stronger (water stage Dresden 877 cm) than the 1784 flood.

2.1.1.2. Dry Intervals

[13] Years with a prolonged summer dryness in the Elbe region can be identified in *Weikinn*’s [1958, 1960, 1961, 1963, 2000, 2002] source texts and his compilation of droughts [*Weikinn*, 1965]. We focus here on well-documented (three or more entries) droughts after 1500. The summers of 1590 and 1842 were major events, where both years saw dryness also in other parts of Germany [*Glaser*, 2001], Bohemia, and Moravia (J. Munzar, Documentation of drought occurrence in Czechia in the preinstrumental period, workshop paper, preprint, 2003). Notable are also the dry summers in 1509, 1616, 1631, 1706, 1746, 1790, 1800, 1813, 1834, and 1835, most of which are also seen in other parts of Germany, Bohemia, and Moravia.

2.1.1.3. Reliability of C. Weikinn’s Compilation

[14] Although C. Weikinn aimed to compile original sources from witnesses, he also listed other unverified references, not employing historical source interpretation. To reduce possible inhomogeneity effects in the flood chronologies, M03 therefore employed additional sources, required supporting information, and restricted the number of magnitude classes.

Table 1. Comparison of Elbe and Oder Flood Chronologies Based on Entries From *Weikinn* [1958, 1960, 1961, 1963, 2000, 2002] and CLIMDAT[a]

	n_W	n_C
Elbe		
Class 3 events	12	12
Class 2 events	43	31
Class 1 events	140	55
Events not noted by C. Weikinn		3
Oder		
Class 3 events	10	10
Class 2 events	20	13
Class 1 events	83	24
Events not noted by C. Weikinn		11

[a] CLIMDAT data are from *Militzer* [1998]. Time interval, A.D. 1500 to 1799; n_W, number of floods noted by C. Weikinn; n_C, number of floods noted in CLIMDAT.

[15] However, it would be a step further to estimate how close the obtained chronologies are to the truth. Since the truth is hidden, we constructed an alternative Elbe flood record using CLIMDAT [*Militzer*, 1998], a climate database of historically and critically reviewed documents. CLIMDAT focuses on central and eastern Germany, Poland, and the Czech Republic, covers the interval A.D. 1500 to 1799, and contains over 19,000 entries.

[16] The comparison (Table 1) shows 100% agreement (“Weikinn’s” Elbe floods listed in CLIMDAT) for exceptionally strong floods (class 3) and good agreement for class 2 floods. This is confirmed by the flood occurrence rates calculated from the C. Weikinn sources and CLIMDAT, which are not significantly different within the confidence band (see below). On the other hand, only 39% of minor Elbe floods listed by C. Weikinn can be found in CLIMDAT. Elbe floods listed by CLIMDAT but not by C. Weikinn are very few (Table 1) and likely of minor magnitude.

[17] In the case of class 1 or class 2 floods, we note that it is not a priori clear whether C. Weikinn’s compilation or CLIMDAT is closer to the truth. Using mixtures of verified/unverified text sources in compilations such as C. Weikinn’s may lead to misdated or even spurious events. However, C. Weikinn and the references he consulted might have had access to information otherwise lost today. Consider as an illustration the ice flood of the Elbe in February 1658, assessed as magnitude 2 by M03. *Weikinn* [1961] lists eight different sources that report floodings at six different locations on the middle Elbe. Additional sources cited by Weikinn report a previous strong ice cover and subsequent thawing in February. They further mention a heavy flood in the tributary Saale. Also, CLIMDAT gives indirect information about strong river freezing in the Erzgebirge area and mentions a sudden thawing that led to a flood in the Saale. CLIMDAT notes that the tributary Prignitz (below Magdeburg, lower Elbe) was influenced by high water stage of the Elbe. However, CLIMDAT fails to report a flood of the middle Elbe in February 1658. Thus a simple “puristic” approach to reconstruct the flood chronology confined to an original source that explicitly notes a flood event on the middle Elbe likely leads to missed events.

2.1.2. Since 1850

[18] The instrumental period started around 1850. *Königliche Elbstrom-Bauverwaltung* [1893] lists monthly

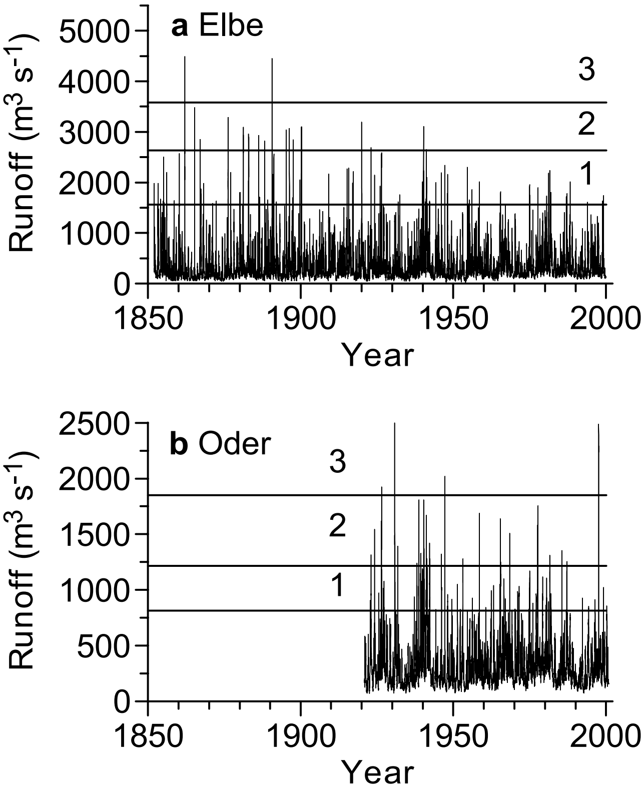

Figure 3. Daily runoff time series. (a) Elbe, station Dresden, covering the interval January 1852 to November 1999. Flood magnitude class bounds (Figure 4) are shown as horizontal lines. Extension of the flood record to September 2002 was achieved using online sources (http://www.wetteronline.de) and *Bundesanstalt für Gewässerkunde* [2002], which gives 4700 m^{3}s^{-1} for the August 2002 flood. The Dresden time series exhibits high correlations with daily runoff series from Elbe stations Děčín (70 km upstream, November 1887 to October 1990, lag = 0 days, r^2 = 0.98) and Barby (240 km downstream, November 1899 to December 1999, lag = 2 days, r^2 = 0.91). (b) Oder, station Eisenhüttenstadt, covering the interval November 1920 to October 2000, exluding January–June 1945. Extension of the flood record to September 2002 was achieved using online sources (http://www.wetteronline.de). *Meteorologischer und hydrologischer Dienst der Deutschen Demokratischen Republik* [1953b] and *UNESCO* [1971] were consulted to verify that no flood had occurred during the interval of missing runoff data. The Eisenhüttenstadt time series exhibits a high correlation with daily runoff series from Oder station Połęcko (25 km upstream, January 1946 to December 1987, lag = 0 days, r^2 = 0.84).

maximum water stage at the stations Dresden, Mühlberg, Torgau, Wittenberg, Rosslau, Barby, and Magdeburg. Daily runoff values at Dresden from January 1852 (Figure 3a) onward are available from the Global Runoff Data Centre (Koblenz, Germany).

[19] Runoff was inferred via stage and stage-runoff relations. These relations were established using explicit measurements of runoff by means of velocity measurements across the river cross section, see also *Königliche Elbstrombauverwaltung* [1898]. The accuracy of a flood record at a particular station, therefore, depends on (1) the accuracy of the stage-runoff relation at upper (flood) values, (2) how frequently relations were updated, and (3) how stable stage-runoff relations were over time. *Helms et al.* [2002a] analyzed several Elbe stations in Germany with regard to the above accuracy requirements (see *Helms et al.* [2002b] for an English summary). From six middle Elbe stations (namely Dresden, Torgau, Wittenberg, Aken, Barby, and Magdeburg), Dresden, followed by Barby, was of the highest quality in terms of above requirements. However, the stage-runoff relation was updated less frequently before 1960, and the stage-runoff ratio exhibited a slow increase over the interval. This may have led to minor systematic errors in inferred runoff for the early part of the instrumental period. Taking into account the widths of magnitude classes (Figure 4a), it can be assumed that this had no major effect on the reconstructed Elbe flood magnitude record. More information on stage-runoff relations for the Elbe is given by *Königliche Elbstrombauverwaltung* [1898], *Bundesanstalt für Gewässerkunde* [2000], and *Sächsisches Staatsministerium für Umwelt und Landwirtschaft* [2002].

2.1.2.1. Exceptionally Strong Floods

[20] Three class 3 events were found for the interval from 1850 to the present. The February 1862 event (824 cm stage or 4490 m^{3}s^{-1} runoff at Dresden) was an ice flood. The September 1890 event (837 cm stage, 4450 m^{3}s^{-1} runoff) was a flood caused by extended rainfall in southern Bohemia. *Königliche Elbstrombauverwaltung* [1898] describes runoff inference for both events. For the August 2002 event (940 cm stage, 4700 m^{3}s^{-1} runoff), values are given by *Bundesanstalt für Gewässerkunde* [2002]. The runoff value might be a lower bound because it was not possible to carry out velocity measurements over the whole river width (H. Engel, Bundesanstalt für Gewässerkunde, personal communication, 2002). The meteorological cause of the August 2002 flood was a pressure low that traveled on a path displaced somewhat to the north of Zugstrasse Vb (Figure 1). The low remained stationary above the catchment areas of both the Elbe and, to the south, the Danube for several days, leading to prolonged rainfall. See *Ulbrich et al.* [2003a, 2003b] for more details.

2.1.2.2. Dry Intervals

[21] Years with a dry summer in the middle Elbe region were identified in the runoff record from Dresden. The 5 driest years in this 150-year period, corresponding to the 12 events in the 350-year documentary period (section 2.1.1.2), are 1863 (118 m^{3}s^{-1} average runoff during May–October), 1865 (107 m^{3}s^{-1}), 1921 (116 m^{3}s^{-1}), 1934 (103 m^{3}s^{-1}), and 1947 (91 m^{3}s^{-1}). With the exception of 1863, these years are also listed by *Glaser* [2001] on climate in Germany.

2.1.2.3. Ice Floods

[22] Continuous data on ice conditions in the Elbe from 1850 to 1930 and 1970 to 2002 were not available to M03. For the period 1930–1970, detailed information is given in the various yearbooks [*Preußische Landesanstalt für Gewässerkunde und Hauptnivellements*, 1933, 1934, 1935a, 1935b, 1936, 1937, 1938; *Landesanstalt für Gewässerkunde und Hauptnivellements*, 1940, 1942; *Forschungsanstalt für Schiffahrt, Gewässer- und Bodenkunde*, 1949, 1950, 1951; *Meteorologischer und hydrologischer Dienst der Deutschen Demokratischen Republik*, 1952a, 1952b, 1952c, 1953a,

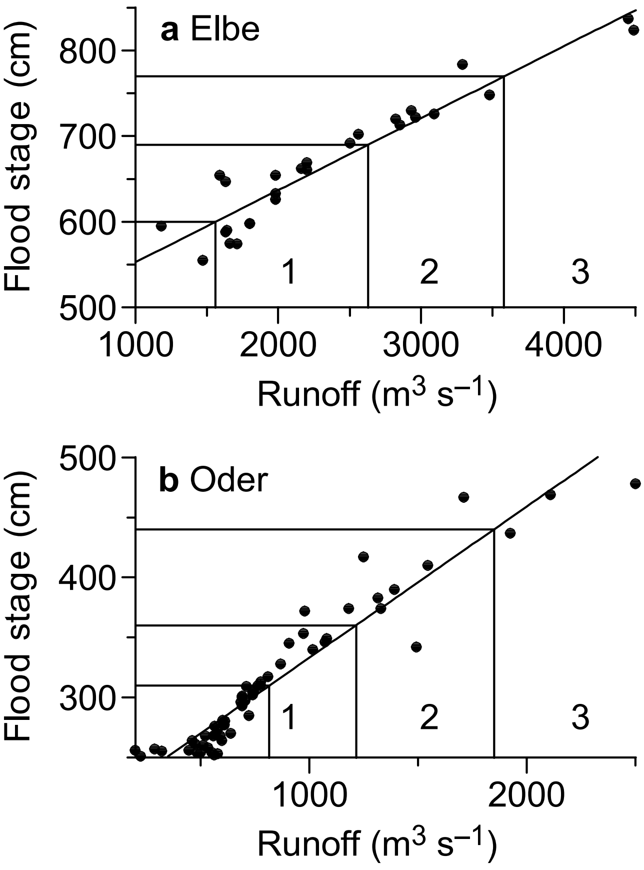

Figure 4. Classification of flood magnitudes (1, minor; 2, strong; 3, exceptionally strong) using linear regressions between flood stage and inferred runoff. (a) Elbe, station Dresden, 1852–1892, $n = 27$, $r^2 = 0.90$, $\sigma_s = 24$ cm, $\sigma_r = 286$ m^{3}s^{-1}; thresholds, 600/690/770 cm and 1560/2630/3580 m^{3}s^{-1}. (b) Oder, stations Krosno (stage) and Eisenhüttenstadt (runoff), 1891–1936, $n = 58$, $r^2 = 0.91$, $\sigma_s = 18$ cm, $\sigma_r = 143$ m^{3}s^{-1}; thresholds, 310/360/440 cm and 815/1215/1850 m^{3}s^{-1}. Here, n, data size; r, coefficient of determination (equals correlation coefficient), σ_s (fit uncertainty in stage) = $(\chi^2/(n-2))^{1/2}$; χ^2, sum of squares; σ_r (fit uncertainty in runoff) = σ_s/slope. In Figures 4a and 4b, the widths of magnitude classes are ~3–4 times larger than the fit uncertainties.

1953b, 1953c, 1954a, 1954b, 1955a, 1955b, 1956a, 1956b, 1957, 1958, 1959, 1961, 1962, 1963; *Institut für Wasserwirtschaft (Berlin-Ost)*, 1964, 1967, 1968, 1969, 1970, 1971, 1974, 1976a, 1976b, 1977, 1979], allowing unambiguous assessment as to whether river freezing was strong enough (ice thickness, duration, and extent of ice sheet) to severely enhance a flood. That was the case only for two winter floods: March 1940 and March 1947. The other 11 winter floods of the Elbe in 1930–1970 (January 1932, December 1939, November 1940, February–April 1941, March 1942, April 1944, February 1946, December 1947 to February 1948, December 1954, March 1955, and March 1956) cannot be considered as "ice floods."

2.1.2.4. Reliability of Flood Record

[23] The middle Elbe flood record in 1850–2002 is assessed as being of excellent quality owing mainly to the Dresden runoff time series. The main reasons are as follows: (1) The record (daily values) starts as early as 1852. (2) No data gaps exist. (3) The stage-runoff relation has a high accuracy and a good stability over time. (4) The high correlations between Dresden runoff and, on the other hand, the series from Barby or Děčín, attest that Dresden is highly representative for the middle Elbe. (5) The abundant availability of stage values for Dresden from the historical period support homogeneity of constructed flood record across 1850.

2.2. Oder Floods

2.2.1. Historical Period

[24] Since the C. Weikinn documentary sources end with the year 1850 and continuous runoff data exist only from 1920 (section 2.2.2), M03 used a number of town chronicles and other descriptions to improve coverage of historical Oder floods: *Gimmler* [1928] on Maltsch (today: Malczyce) (information about floods in ~1400–1903), *Schmidt* [1922] on Grünberg (today: Zielona Góra) (~1400–1911), *Partsch* [1896, 1911] on Silesia (~1445–1903), *Schulz* [1926, 1930, 1961] on Neusalz (today: Nowa Sól) (~1550–1903), *Mengel* [1930, 1934] on the Oderbruch (lower part of middle Oder) (1850–1920), and *Kociński* [1997] on Silesia (1901–1997).

[25] The observation interval of Oder floods starts at A.D. 1269. Abundant information on floods in the historical period came from the stations Racibórz, Kożle, Opole, Ujście Nysy, Brzeg, Wrocław, Brzeg Dolny, Malczyce, Ścinawa, Głogow, Nowa Sól, Cigacice, Krosno, Połęcko, Eisenhüttenstadt, Frankfurt an der Oder, Słubice, and Kostryn; also Gozdowice and Schwedt (lower Oder) were consulted. Supporting information by tributaries on the regional extent of an Oder flood came mostly from the rivers Nysa Kłodzka, Kaczawa, and Bóbr. *Fischer* [1907] gives historical flood stages at various Oder stations; stage values and measured runoff values are provided by *Bureau des Ausschusses zur Untersuchung der Wasserverhältnisse in den der Überschwemmungsgefahr besonders ausgesetzten Flußgebieten* [1896] (hereinafter referred to as BUREAU).

[26] The number of doubtful Oder flood events (all class 1) is 33.

2.2.1.1. Exceptionally Strong Floods

[27] Fifteen class 3 events were found for the historical period. The July–August 1496 event was supported by reports about strong rainfall. The Oder saw the August 1501 event (as did the Elbe), with one report relating it to huge rainfall at the end of that month. Prolonged rainfall (several weeks) caused the July–September 1515 flood. For the March 1565 event, reports about a hard winter exist, but none about freezing of or ice jam in the Oder. For the July 1595 event, rainfall was reported, and BUREAU gives 525 cm flood stage at Krosno. For the July 1675 event, rainfall was noticed for the area of the river Kwisa in the Oder region. For the March–April 1698 event there were many reports, but none about ice. BUREAU gives 525 cm stage (Krosno). The February–April 1709 event was an ice flood. For the May 1729 event, strong rainfall is mentioned, and BUREAU gives 525 cm stage (Krosno). *Militzer et al.* [1999] relate the June–August 1736 event to prolonged rainfall caused by a Zugstrasse Vb-low (512 cm stage). The April 1785 event was an ice flood, 479 cm stage at Krosno

(BUREAU). *Mann* [1905] describes rainfall and flooding (>440 cm at Krosno) of the August–September 1813 event in great spatial and temporal detail. The March 1830 event was an ice flood. BUREAU gives 488 cm Oder flood stage at Krosno. The September 1831 event had long rainfall, and BUREAU gives 475 cm stage. The March 1838 event had 524 cm (BUREAU) at Krosno and reports from several locations about the breaking of a strong ice sheet.

2.2.1.2. Dry Intervals

[28] The Oder region [*Weikinn*, 1958, 1960, 1961, 1963, 1965, 2000, 2002] experienced major dryness in summers 1590 and 1842 (as did the Elbe and other regions). Also notable are the dry summers in 1719 and 1834.

2.2.1.3. Reliability of C. Weikinn's Compilation

[29] The comparison between C. Weikinn's compilation and CLIMDAT (Table 1) shows 100% agreement ("Weikinn's" floods listed in CLIMDAT) for exceptionally strong floods (class 3) and good agreement for class 2 floods. This is confirmed by the flood occurrence rates calculated from both sources, which are not significantly different within the confidence band (see below). Only 29% of minor Oder floods listed by C. Weikinn can be found in CLIMDAT. Similarly as for the Elbe, floods of the Oder listed by CLIMDAT, but not by C. Weikinn, are very few (Table 1) and are likely of minor magnitude.

2.2.2. Since 1850

[30] Availability of measured stage or runoff data for the Oder is worse than for the Elbe. *Fischer* [1907] gives stages from various stations, but only for summer floods. *Oderstrombauverwaltung* [1907] gives yearly maximum/minimum water stage at various Oder stations for 1854–1904; *Oderstrombauverwaltung* [1907, 1930, 1931, 1934, 1938] gives monthly maximum/minimum water stage for 1905–1936. Runoff measurements from Eisenhüttenstadt are reported by BUREAU for three floods in the 1890s; runoff from Eisenhüttenstadt for the July 1903 flood is given by *Grünewald et al.* [1998]. Daily runoff values, mostly inferred via stage, from November 1920 (Eisenhüttenstadt) are available via Global Runoff Data Centre. (A gap in daily runoff data from January to June 1945 was closed using monthly data from *Meteorologischer und hydrologischer Dienst der Deutschen Demokratischen Republik* [1953b] and *UNESCO* [1971].)

[31] Magnitude classification of Oder floods (historical and instrumental period) was achieved by M03 using a regression between flood stage at Krosno and runoff at nearby station Eisenhüttenstadt (Figure 4b). The good correlation (r^2 = 0.91) for the 1904–1936 period indicates some stability in the stage-runoff relation at upper values. Also, the magnitude class widths are clearly larger than the stage-runoff uncertainties (Figure 4b). However, detailed information on the accuracy of the stage-runoff relation is not available owing to war chaos (after World War II) and divided responsibilities (Germany/Poland). The data quality of the record of minor (class 1) winter floods of the Oder between 1850 and 1920 is therefore likely reduced in comparison with other records. It is suspected that archival studies using material from the major city at the Oder, Wrocław, could improve data quality significantly.

2.2.2.1. Exceptionally Strong Floods

[32] Nine class 3 events were found for the interval from 1850 to the present.

[33] After the summer flood in August 1854 (555 cm stage at Krosno), the following winter floods occurred: April 1855 (459 cm stage), February–March 1876 (505 cm stage) and March 1891 (467 cm stage at Krosno or 1710 m^3s^{-1} runoff at Eisenhüttenstadt), preceded by an event in 1871 (447 cm). This latter flood appears prominent in the yearly maximum stage records for various stations [*Oderstrombauverwaltung*, 1907] but is not mentioned elsewhere. No information on ice conditions was available. Assuming that *Fischer* [1907], writing on summer floods, had not missed it, M03 inferred that 1871 was a winter flood. July 1903 (469 cm stage at Krosno or 2110 m^3s^{-1} runoff at Eisenhüttenstadt) is the last in the detailed hydrographic and meteorological description by *Fischer* [1907] of summer floods in the Oder from 1813 to 1903. He, and also *Hellmann and von Elsner* [1911], popularized the causal role of the Zugstrasse Vb for these types of floods. The October 1915 flood hit the middle Oder at Wrocław and places below (468 cm stage at Krosno), as documented in the monthly maximum stage records [*Oderstrombauverwaltung*, 1930]. The June–August 1926 flood (437 cm stage at Krosno) is the first class 3 event to be documented by the daily runoff record from Eisenhüttenstadt (1925 m^3s^{-1}). October–December 1930 (478 cm stage at Krosno or 2500 m^3s^{-1} runoff at Eisenhüttenstadt) was one of the largest events in record for the Oder (not enhanced by ice jam). The March–April 1947 event was similar, and it also showed the violence of an ice flood despite a lower runoff value (2020 m^3s^{-1} at Eisenhüttenstadt); see *Trömel* [1997] and *Grünewald et al.* [1998]. The next class 3 event was the July 1997 flood (2490 m^3s^{-1} runoff at Eisenhüttenstadt), described in detail by *Grünewald et al.* [1998].

2.2.2.2. Dry Intervals

[34] Years with a dry summer in the middle Oder region were identified in the daily runoff record from Eisenhüttenstadt. The 2 driest years in this 80-year period that might be comparable to the 4 events in the 350-year documentary period (section 2.2.1.2), are 1933 (124 m^3s^{-1} average runoff during May–October) and 1992 (128 m^3s^{-1}). For the period 1850–1920, the more coarsely resolved data from *Oderstrombauverwaltung* [1907, 1930] indicate 1904 and 1921 as the two driest years; the *Glaser* [2001] work, on climate in Germany, notes the latter and gives 1902 (instead of 1904), indicating a possible misprint.

2.2.2.3. Ice Floods

[35] M03 gave information as to whether or not winter floods were enhanced by ice jams during the period 1930–1970. Here, we extend this period backward using data from *Oderstrombauverwaltung* [1930, 1931]. For the period 1911–1970, the data given there and in the yearbooks (see section 2.1.2.3) indicate that four winter floods were likely enhanced by breaking river ice: March–April 1924, March–April 1940, March–April 1942, and March–April 1947. The 28 other winter floods of the Oder in 1911–1970 (February–March 1911, March–April 1915, December 1915 to January 1916, January 1917, March–May 1917, January 1918, December 1919 to February 1920, December 1922 to February 1923, January 1927, April 1927, October–December 1930, March–May 1931, March 1937, January–February 1938, April 1939, November–December 1939, February–June (!) 1941, December 1941, April 1944, February–March 1946, January–March 1948, April 1952, February–March

1953, March 1956, March 1963, March 1965, February 1967, and March–April 1970) cannot be considered as "ice floods."

2.2.2.4. Reliability of Flood Record

[36] The middle Oder flood record in 1850–1920 is of minor quality mainly because neither continuous data in daily resolution nor detailed documentary data are yet available. The fact that the regression between runoff and stage (Figure 4b) had to use data from two different stations (Krosno, Eisenhüttenstadt) is less important because these are close to each other and the correlation is high. The middle Oder flood record in the period from 1920 to 2002 is assessed as being of clearly better quality than the record in the earlier period, although the quality of the Elbe flood record from Dresden might be superior. (1) Only a minor data gap exists in daily runoff for the Oder. (2) Some stability of the stage-runoff relation is indicated by the data in Figure 4b, although detailed information does not seem to be available. (3) The stage values for some Oder floods at Krosno give credence to the homogeneity of constructed flood record across 1850.

2.3. Atmospheric Pressure

[37] Reconstructions of SLP and 500 hPa height (z_{500}) from 1999 back to December 1658 at monthly resolution were carried out by *Luterbacher et al.* [2002] using a combination of early instrumental data (pressure, temperature, and precipitation) and documentary proxy data from Eurasian sites. The relationships between SLP or z_{500}, on the one hand, and the proxy data, on the other, were derived for a calibration period (1901–1960) using a regression technique (principal component analysis) and verified for the period 1961–1990. The spatial resolution is 5.0 by 5.0 degrees (2.5 by 2.5 degrees) for the SLP (z_{500}) data over an area ranging from 30°W to 40°E and 30°N to 70°N.

3. Methods

[38] First, we review various methodical approaches that have been used to analyze trends in the occurrence of extreme events (such as floods), that is, to identify time periods during which extreme events occurred more often than during other periods. We list advantages and disadvantages of approaches and conclude that kernel occurrence rate estimation, employed by M03, is one of the most powerful approaches because it imposes few restrictions, allows for nonlinear and nonmonotonic trends, and provides reliable error bands. Also, the described statistical test for trend in the occurrence rate was found by M03 to be a helpful method to confirm results obtained from kernel estimation.

[39] We further give a correlation method for quantifying the relation between flood occurrences, and, on the other hand, SLP or z_{500} atmospheric variables.

3.1. Trends in Occurrence of Extreme Events: Regression Approaches

[40] Regression approaches use quasi-continuous data $x(t)$ (e.g., average daily runoff) over a time period. The recipe then is to fit a parametric model (e.g., linear) to the data and take the slope to indicate trend, or to perform nonparametric tests, such as Mann-Kendall's or Spearman's for trend; see *Press et al.* [1992].

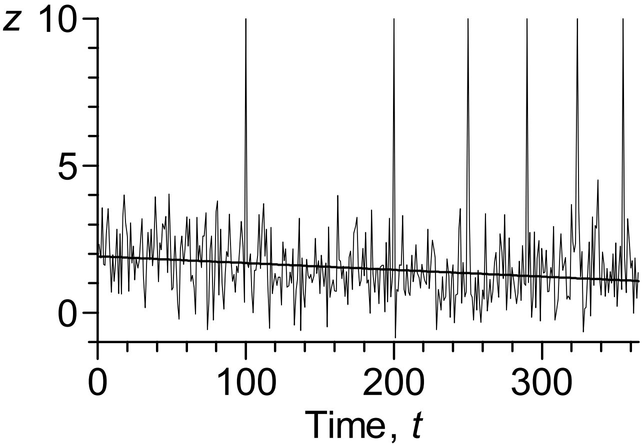

Figure 5. Failure of regression-based approaches to detect trends in occurrence rate of extreme events. The artificial time series (thin line) is $z(i) = 2 - (1/365)\, t(i) + \epsilon(i)$, with $i = 1, \ldots, 365$, $t(i) = i$, and $\epsilon \sim N(0, 1)$ (standard normal distribution); $z(100) = z(200) = z(250) = z(290) = z(324) = z(355) = 10.0$ was set subsequently to simulate extreme events occurring at a linearly increasing rate. The least squares linear regression (thick line) yields a significant (within 1-σ standard deviation) negative slope.

[41] Advantages of regression approaches are that the time dependence of the series is taken into account and no arbitrary time intervals are formed. The disadvantage is that regressions model the mean of the time series rather than the extremes. A situation is mathematically conceivable in which the mean shows a downward trend and the extremes show an upward trend in occurrence. A regression, although influenced by the extremes, would give quite the wrong result about the occurrence of extremes (Figure 5). This effect can be reduced, but not corrected for, by taking daily maxima instead of daily averages.

3.2. Trends in Occurrence of Extreme Events: Peak-Over-Threshold (POT) Approaches

[42] The general idea (POT advantage) is to avoid the deficiencies of regression approaches and analyze the data of interest: the extremes. From quasi-continuous data $x(t)$, the extremes can be detected by applying a threshold and taking those events that lie above it. Negative extremes, below a threshold, can be analyzed analogously. One example is to study the occurrence of droughts. The constraint "nonnegative runoff" has then to be taken into account when performing an extreme value analysis (see below).

[43] Evaluation of the runoff thresholds (Figure 3) was determined by values found from the analysis of the documentary period (sections 2.1 and 2.2). In principle, thresholds can be determined by an extreme value analysis [*Embrechts et al.*, 1997] of $x(t)$. For example, the 25-year return value was applied in M03 to precipitation time series. Note that the standard deviation of $x(t)$ is a particularly bad (nonrobust) estimator for determining

threshold because it is heavily influenced by the extreme values [*Lanzante*, 1996].

[44] The underlying model of the POT approach is the Poisson process [*Leadbetter*, 1991], which is described by parameter λ (occurrence rate), that is, the probability per time interval that the threshold is exceeded. The Poisson process assumes statistical independence of events. Satisfying this when applying the POT approach to daily runoff time series, $x(t)$, requires taking only the flood peak, $\max(x)$, and not points (which might also lie above the threshold) within a time neighborhood. The size of the neighborhood is determined by the time over which a runoff value "remembers" past values, typically a few weeks (see Figure 11 for an example). Both Dresden and Eisenhüttenstadt runoff series exhibit only very few flood peaks that are ambiguous in terms of independence. The general case, which is important for studying nonstationary phenomena such as changes in the occurrence of extreme events, is the inhomogeneous Poisson process [*Cox and Lewis*, 1966], which has a time-dependent occurrence rate, $\lambda(t)$.

3.2.1. Interval Comparison Technique

[45] The simplest POT technique compares two time intervals with respect to the properties of the statistical distribution that describe the extreme values found inside. Typically chosen is the return period, τ, which is the expected time for an extreme event to occur. $\tau = 1/\lambda$ can either be estimated by fitting a parametric extreme value distribution to the data or, less accurately, by dividing the interval length by the number of extremes.

[46] Extreme value theory is a well-elaborated statistical field that can provide accurate estimations and error bars (although the latter were hardly reported in the flood literature reviewed in preparing this manuscript). The major disadvantage of the interval technique is that only two estimates, representing two time intervals, are formed from a possibly long time series. Details of the time dependence in the occurrence of extreme events are missed, such as nonstationarities within an interval. Further, interval selection is arbitrary. The danger is in selecting those intervals that seem to best fit what was anticipated before the analysis.

3.2.2. Continuous-Time Techniques

[47] Evidently, a technique implementing the POT approach without degrading the time information by selecting two coarse intervals is preferred. Such a technique can be implemented in two ways. First, the parametric model describes the occurrence of extremes over continuous time by a function. Second, the nonparametric implementation uses continuously shifted intervals to explore the time dependence.

3.2.2.1. Parametric Implementations

[48] *Frei and Schär* [2001] applied the logistic regression model

$$\lambda(t) = \exp(a + b \cdot t)/[1 + \exp(a + b \cdot t)] \qquad (1)$$

to detect trends in the occurrence of extreme precipitation in the Alpine region. Parameters a and, notably, b (trend parameter) can be estimated from the data using a maximum likelihood principle. Other models, which include a stepwise change in $\lambda(t)$, have also been proposed [*Loader*, 1992].

[49] A particularly simple model,

$$\lambda(t) = \exp(a + b \cdot t), \qquad (2)$$

has been used by *Cox and Lewis* [1966] to test the null hypothesis H0: "$b = 0$" (constant occurrence rate) against H1: "$b > 0$" (increasing occurrence rate). They showed that under H0, the test statistic

$$u = \left[\sum T(i)/n - (t_2 + t_1)/2\right] \Big/ \left[(t_2 - t_1)(12n)^{-1/2}\right] \qquad (3)$$

becomes, with increasing n, rapidly standard normally distributed in shape. $T(i)$, $i = 1, \ldots, n$, are the extreme event dates, n is the data size, and $[t_1, t_2]$ is the observation interval. For example, a value of $u = +1.65$ corresponds to a one-sided P value (probability that a standard normal distribution produces a value $>u$) of 0.049, meaning that the upward trend is significant at the 95% confidence level.

[50] It is evident that the parametric regression technique is a substantial improvement over interval comparison, yielding estimates of $\lambda(t)$ that are superior in terms of time resolution. However, the exponential regression family, which arises from the transformation of the probability interval [0, 1] to the real axis, limits the applicability of the current parametric implementations to rather simple forms of $\lambda(t)$ (constant, monotonic increase, etc.). The parametric implementation is therefore well suited for analyzing climatic extremes over shorter timescales (e.g., the past decades in the case of extreme precipitation and flood events). There it can reveal significant upward [*Frei and Schär*, 2001] or downward (M03) trends.

[51] It is, however, important to extend the view to longer timescales (e.g., the past centuries in the case of extreme precipitation and flood events) to successfully analyze the occurrence of climatic extremes and the relation to other climate variables. On such timescales, more complicated functional forms of $\lambda(t)$ can be expected, which are not accessible with simple parametric implementations.

3.2.2.2. Nonparametric Implementation: Kernel Occurrence Rate Estimation

[52] The nonparametric kernel implementation [*Diggle*, 1985] estimates the occurrence rate as

$$\hat{\lambda}(t) = h^{-1} \sum_{i=1}^{n} K([t - T(i)]/h), \qquad (4)$$

where K is the kernel function and h is the bandwidth (the "hat" denotes the estimate). The interval comparison (section 3.2.1) can be seen as a technique that adopts a uniform kernel function ($K(y) = 1/(2\,h)$ for $|y| \leq h$ and $K = 0$ otherwise) and estimates λ at only two points in time, t. Higher time resolution is achieved by letting t run quasi-continuously within the observation interval $[t_1, t_2]$, as the running mean does in the case of a uniform kernel. Using a smooth kernel function yields a more realistic smooth estimate of the occurrence rate. M03 used a Gaussian kernel ($K(y) = \exp(-y^2/2)/(2\pi)^{1/2}$) that allows one to calculate $\hat{\lambda}(t)$ efficiently in Fourier space [*Silverman*, 1982].

[53] Boundary effects (underestimation of $\hat{\lambda}(t)$ near t_1 and t_2) can be considerably reduced by generating pseudodata, $T'(i)$, outside of $[t_1, t_2]$ before occurrence rate estima-

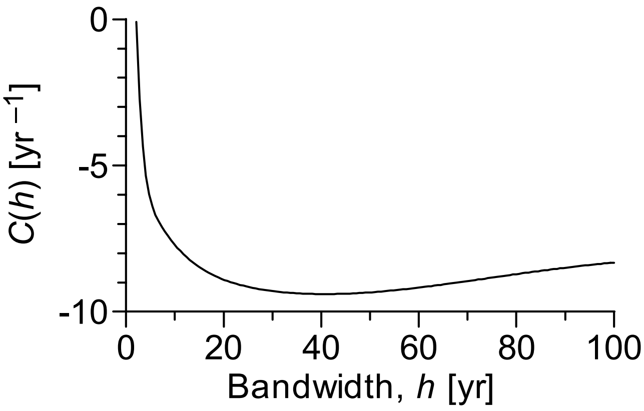

Figure 6. Determination of bandwidth, h, for kernel occurrence rate estimation, Elbe winter floods (magnitude class 2–3). The cross-validation function (equation (5)) has a minimum at h = 41 years.

tion. (In equation (4), n is replaced by $n^\dagger = n + n'$, where n' is the number of pseudodata.) For that, "reflection" ($T'(i) = t_1 - [T(i) - t_1]$ on the left bound and analogously on the right bound) is a straightforward method. *Cowling and Hall* [1996] give further, more advanced pseudodata generation methods. Since pseudodata generation is equivalent to an extrapolation of the empirical distribution function, results at the boundaries should be judged cautiously. M03 used a relatively small bandwidth (see next paragraph) to keep boundary effects small and found (not shown) the various pseudodata generation methods applied to Elbe and Oder floods to yield similar results at the boundaries.

[54] Bandwidth (h) selection determines bias and variance properties of the occurrence rate estimation and is therefore a crucial step. M03 invoked the cross-validation bandwidth selector of *Brooks and Marron* [1991], that is, the minimizer of

$$C(h) = \int_{t_1}^{t_2} \hat{\lambda}(t)^2 dt - 2\sum_{i=1}^{n^\dagger} \hat{\lambda}_i\left(T^\dagger(i)\right), \tag{5}$$

where

$$\hat{\lambda}_i(t) = \sum_{j\neq i,\, j=1}^{n^\dagger} K\left(t - T^\dagger(j)\right) \tag{6}$$

and where $T^\dagger$ are original data (T) augmented by pseudodata (T'). The cross-validated bandwidth can be seen as a compromise between small h (large variance and small bias of $\hat{\lambda}$) and large h (small variance and large bias). Figure 6 shows the cross-validation function $C(h)$ for Elbe winter floods (class 2–3), which has a minimum at h = 41 years. Other flood data analyzed by M03 (class 1–3; summer; Oder) gave similar values. Results (section 4) are calculated using a smaller value, h = 35 years, for all flood records to facilitate comparability and to reduce boundary effects.

[55] A confidence band around $\hat{\lambda}(t)$ is essential for interpreting results. For example, it might be asked if a low in $\hat{\lambda}(t)$ is real or came instead by chance into the data. A confidence band can be obtained using bootstrap simulations [*Cowling et al.*, 1996] as follows:

[56] 1. From the set $\{T^\dagger\}$ of size $n^\dagger$, draw with replacement a simulated set of flood dates, $\{T^*\}$, of same size.

[57] 2. Calculate $\hat{\lambda}^*(t)$ after equation (4) using simulated data and same h.

[58] 3. Repeat the procedure simulation-estimation until 2000 versions of $\hat{\lambda}^*(t)$ are available.

[59] 4. A simple, percentile-based confidence interval (of level α) at time t is given by the central α values of ordered $\hat{\lambda}^*(t)$. For example, for α = 90%, it is given by the interval between the 100th and 1900th largest values.

[60] 5. The confidence band is given by the confidence intervals over time $t \in [t_1, t_2]$.

[61] 6. *Cowling et al.* [1996] describe construction of a percentile-*t* type confidence band (denoted as "Type 1" and used by M03), which has higher accuracy than the percentile-based band.

[62] *Cowling et al.* [1996] give further bootstrap schemes and confidence band types, which have properties similar to those of the method shown here.

[63] The methods of kernel occurrence rate estimation with bootstrap confidence bands and hypothesis test have been implemented into the computer program XTREND [*Mudelsee*, 2002a], which was used in the calculations for M03 and the present paper.

3.3. Correlation Between Occurrence of Floods and Climate

[64] Kernel-estimated time-dependent flood occurrence rate (section 3.2.2.2) allows the identification of highs and lows in flood risk, which can be visually related to climatic conditions (section 4.1). For evaluating the influence of past, and predicting the influence of future, climatic changes on flood risk, however, it is important to quantify the relation between flood occurrence and forcing climate variables. This is done in the present paper by calculating the correlations between, on the one hand, Elbe or Oder floods (sections 2.1 and 2.2) and, on the other, gridded SLP or z_{500} data (section 2.3).

[65] Since use of the occurrence rate, $\hat{\lambda}(t)$, would seriously hamper the accuracy of estimated correlations because of the smoothing (Gaussian kernel) and the high degree of serial dependence of $\hat{\lambda}(t)$, "binary" flood time series were formed as follows. Consider as an example the relation between monthly SLP time series ($t(i)$, $x(i)$) and Elbe winter floods ($t(i)$, $y(i)$). Time $t(i)$, $i = 1, \ldots, m = 2045$, counts winter months in 1658–1999; $x(i)$ = SLP; $y(i) = 1$ if a flood (magnitude class $\geq$ 1) occurred at $t(i)$, otherwise $y(i) = 0$. The point-wise biserial correlation coefficient [*Kraemer*, 1982] is

$$r_{\mathrm{pb}} = (pq)^{1/2}(x_1 - x_2)/s, \tag{7}$$

where p is the proportion of the y sample with $y = 1$; $q = 1 - p$; x_1 and x_2 are mean x values having $y(i) = 1$ and 0, respectively; and s^2 is the sample variance of x.

[66] To test significance (P, tail probability) of an individual correlation (single grid point), the statistic

$$t_{\mathrm{pb}} = (m_{\mathrm{eff}} - 2)^{1/2} r_{\mathrm{pb}} \Big/ \left(1 - r_{\mathrm{pb}}^2\right)^{1/2} \tag{8}$$

was used. Under the assumptions of (1) normally distributed x (which is excellently fulfilled in the case of SLP and z_{500})

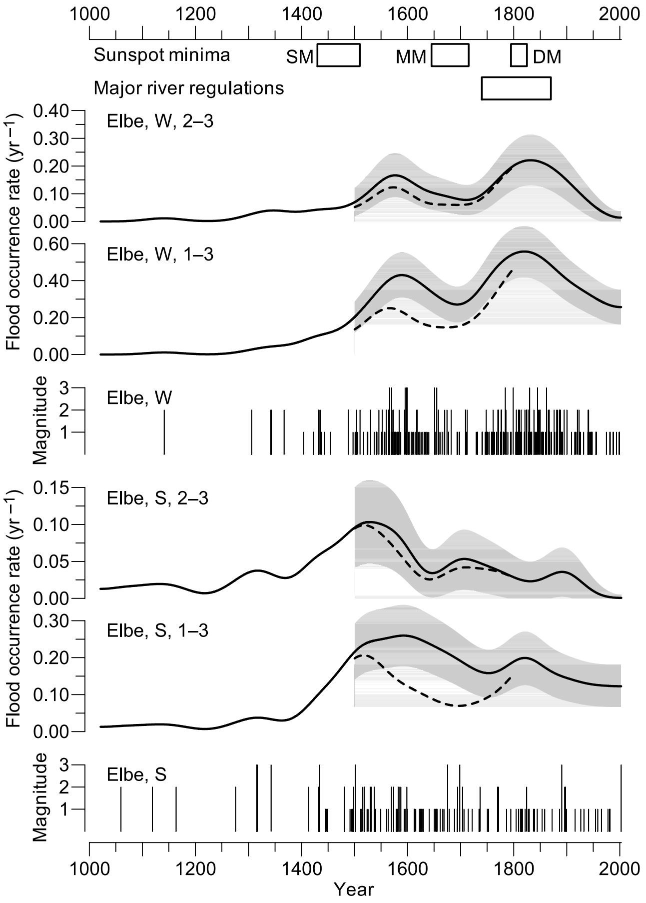

Figure 7. Occurrence of Elbe floods during winter (W; November–April) and summer (S; May–October), for all flood magnitudes (classes 1–3) and heavy floods only (classes 2–3). Kernel estimation (section 3.2.2.2) using a bandwidth of 35 years is applied to the flood dates (shown as bar charts), obtained from measurements and C. Weikinn's documentary data (section 2.1) to calculate time-dependent flood risks, $\widehat{\lambda}(t)$ (solid lines) with bootstrap 90% confidence band (shaded). Records before 1500 are likely not homogeneous (no confidence bands shown). Occurrence rates using documentary entries from database CLIMDAT for 1500–1799 are shown as dashed lines. Also shown are time periods of sunspot minima (SM, Spörer Minimum; MM, Maunder Minimum; DM, Dalton Minimum) taken from *Kurths et al.* [1997] and the time period of major regulations of the river Elbe.

and (2) equal variances of $\{x(i)|y(i) = 1\}$ and $\{x(i)|y(i) = 0\}$ (which is well fulfilled in case of SLP and z_{500}), t_{pb} is distributed [*Kraemer*, 1982] as Student's t with $m_{\mathrm{eff}} - 2$ degrees of freedom. The effective sample size, m_{eff}, quantifies the reduction of the original sample size, m, by positive serial dependence (persistence) in the atmospheric pressure time series [*von Storch and Zwiers*, 1999]. The persistence time (decay period of the autocorrelation function) was estimated using the algorithm of *Mudelsee* [2002b] to be on the order of less than 31 days (SLP) or 73 days (z_{500}). Plugging these values into the algorithm of *Mudelsee* [2003], which determines P values of correlation estimates in the presence of persistence, confirmed that the Student's-t distribution of t_{pb} is valid, with $m_{\mathrm{eff}}/m \approx 0.90$ (SLP) and 0.85 (z_{500}). Ignoring persistence would lead to using $m_{\mathrm{eff}} = m$ and an overestimation of the significance.

[67] To judge the significance of the multiple correlations (the number of grid points, n_{grid}, is 135 (SLP) or 493 (z_{500})), the following iterative procedure was employed.

[68] 1. Analyze grid point with $\max(|r_{\mathrm{pb}}|)$, that means, lowest P. If $n_{\mathrm{grid}} \cdot P < 0.10$, then this correlation is significant (90% confidence level); if not, then stop comparison.

[69] 2. Reduce n_{grid} by 1 and repeat step 1 with second highest $|r_{\mathrm{pb}}|$, etc.

[70] This procedure revealed that values $|r_{\mathrm{pb}}| \geq 0.075$ (SLP) or 0.08 (z_{500}) can be regarded as significant. Ignoring multiplicity of comparison would lead to an overestimation of the significance of found correlations.

4. Results and Discussion

4.1. Flood Occurrence Rates

4.1.1. Historical Period

[71] Figures 7 and 8 show estimated occurrence rates of Elbe and Oder floods, respectively. For both rivers, both winter and summer seasons, and all magnitude classes, estimated flood occurrence rates are very low in the early part of the millennium and increase toward about A.D. 1500. One explanation of those increases is data inhomogeneity. Fewer documents about floods from that period, compared with following periods, were written (before the invention of printing) or have lasted to the day when they were included in secondary compilations (such as C. Weikinn's). This would lead to missed events and an underestimation of flood occurrence rate. Also, perception of extreme events such as floods [*Glaser*, 2001] and the willingness of people to record weather events might have been different before the Copernican science revolution. Another explanation is deforestation, which would have enhanced runoff in the mountainous catchment areas. *Bork et al.* [1998] make a case that the millennium flood of July 1342, which affected many parts of Germany and particularly the Main area [*Tetzlaff et al.*, 2002], was related to deforestation. However, *Bork et al.* [1998] present no evidence of deforestation in the Erzgebirge, Sudeten, or Beskids for the first half of the millennium. *Firbas and Losert* [1949] give results from pollen analysis on bog sediment cores [*Firbas*, 1952] from several sites in the Sudeten and the Erzgebirge. It seems that before the fifteenth/sixteenth century, no significant deforestation had occurred, although the quality of the dating might be debatable. *Firbas and Losert* [1949] also note that during the Little Ice Age the tree line lowered. This makes an interesting link between climate and flood occurrence, which should be explored further using a hydrological model. To summarize, although we cannot definitively rule out deforestation, we cautiously prefer data inhomogeneity as an explanation of the observed increases in flood risk before 1500.

[72] Records after 1500 are likely homogeneous in the case of heavy floods (magnitude classes 2–3). This is demonstrated by the agreement between the C. Weikinn and CLIMDAT-based flood occurrence rates, which are not significantly different within the confidence bands (Figures 7

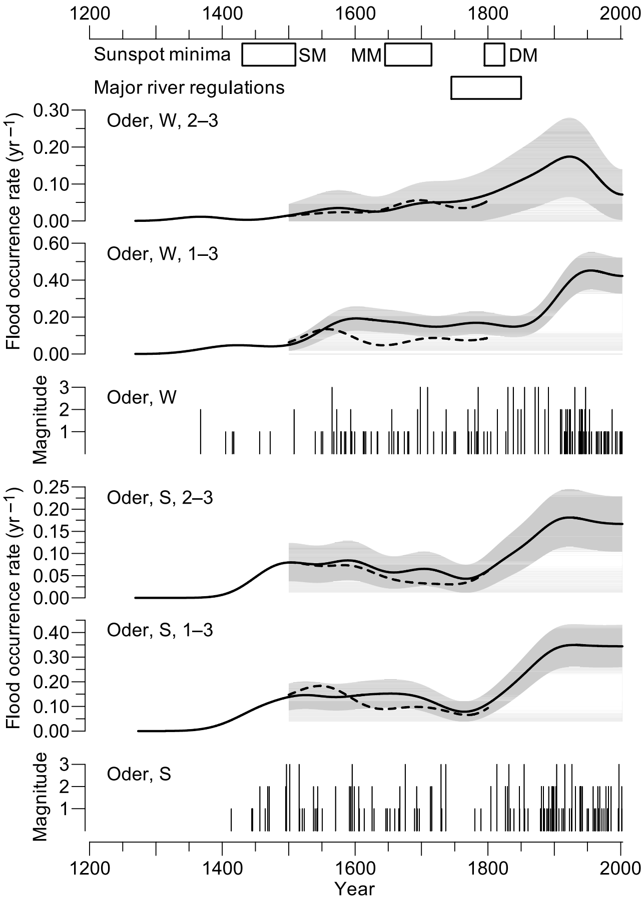

Figure 8. Occurrence of Oder floods during winter (W) and summer (S), for flood magnitudes 1–3 and 2–3. Flood dates are shown as bar charts, and flood occurrence rates are shown as solid lines with 90% confidence bands (shaded); flood occurrence rates calculated using CLIMDAT instead of C. Weikinn's database for 1500–1799 are shown as dashed lines. SM, Spörer sunspot Minimum; MM, Maunder Minimum; DM, Dalton Minimum. Kernel bandwidth is 35 years; see Figure 7 for further explanation.

and 8). When also including minor floods (class 1), CLIMDAT data (1500–1799) produce significantly lower rates than C. Weikinn's data. Since it is not clear which data source is closer to the truth (sections 2.1.1.3 and 2.2.1.3), the interpretation focuses on heavy flood occurrence.

[73] A maximum in flooding rate was reached (both rivers; both seasons; all classes) in the sixteenth century, presumably in its latter half. *Brázdil et al.* [1999] studied floods in central and southwest European rivers and found similar increases, which they attributed to higher precipitation. Also, in the case of the Elbe and the Oder, a wet sixteenth century might be assumed, considering documentary precipitation data from the Czech Republic and the west Sudeten mountains [*Starkel*, 2001] and, at higher temporal but lower spatial resolution, from Germany [*Glaser et al.*, 1999; *Glaser*, 2001].

[74] The subsequent reduction in Elbe winter flood risk to a low at around 1700, significant at the 90% level, could reflect the dry (and cold) European climate of the Late Maunder Minimum [*Luterbacher et al.*, 2001]. Some absence of heavy rains in the Polish/Czech area during that time is noted by *Starkel* [2001]. Also, the Elbe summer flood risk was reduced during that time, but not significantly in the case of heavy floods (Figure 7). The fact that the Oder shows no such Late Maunder Minimum lows in flood risk (Figure 8) points to the spatial variability in flood risk owing to differences in orography [*Brázdil et al.*, 1999]. This is confirmed by the following points: (1) Dates of exceptionally strong floods in these neighboring rivers (sections 2.1.1.1 and 2.2.1.1) show considerable disagreements. (2) Correlation coefficients between the Elbe and Oder flood time series are low (~0.3). (The flood series were constructed using monthly magnitude data with magnitudes for months without a flood set equal to zero. The correlation coefficients were calculated separately for winter and summer, yielding similar results. Analyses of extracted intervals confirm that these relations have not changed over time.)

[75] As regards the relation of solar activity and rainfall, *Starkel* [2001, p. 74], who studied floods and heavy rainfalls in some European regions over the past millennium, observes "an interesting repetition of clusterings of heavy rains at the beginning of each century (ca 1590–1610, 1705–1715, 1800–1815) coinciding with Spörer, Maunder and Dalton solar minima." Note that the time interval given for the Spörer Minimum is around 100 years later than what is found in standard references (such as *Kurths et al.* [1997]). However, also for the other two sunspot minima, our results from the Elbe and Oder (Figures 7 and 8) cannot unambiguously support this observation. We doubt that a solar signal can be deciphered in the presently available data owing to the various error sources (low spatial resolution, limited proxy quality of floods as rainfall gauges).

[76] Major river-engineering work on middle Elbe and middle Oder started in the middle of the eighteenth century. Work on the Oder was initiated by the Prussians in 1745, soon after their invasion of Silesia. The type of river modification was generally limited to removal of trunks and length reduction by straightening [*Oder-Zeitung*, 1925; *Schmidt*, 2000]; dams were also built since earlier times [*Schmidt*, 2000]. It is estimated [*Grünewald et al.*, 1998] that by the end of ~1850, the whole Oder was shortened by about 160 km, or 20%. The type of engineering work on the middle Elbe (from roughly 1740 to 1870) consisted of straightening and removal of small river islands. However, the reduction in length (~60 km [*Schmidt*, 2000]) was clearly less than in the case of the Oder. Integrated over a regional scale (middle Elbe, middle Oder), effects of such engineering work on flood risk, if any, should have been similar, regardless of the river, the season (winter, summer), or the magnitude (1–3, 2–3). Since a rather heterogeneous behavior is found (Figures 7 and 8), we conclude that influences of river engineering on flood risk were only minimal.

[77] During the nineteenth century, the opposite trends prevailed: Elbe flood occurrence rates (especially for winter) show downward trends, which continue to the present (see section 4.1.2), while Oder floods (especially for summer) exhibit upward trends. These different trends could be the mere product of the orographic differences between catchment areas, which were already mentioned. In the case of winter floods, they could also bear a

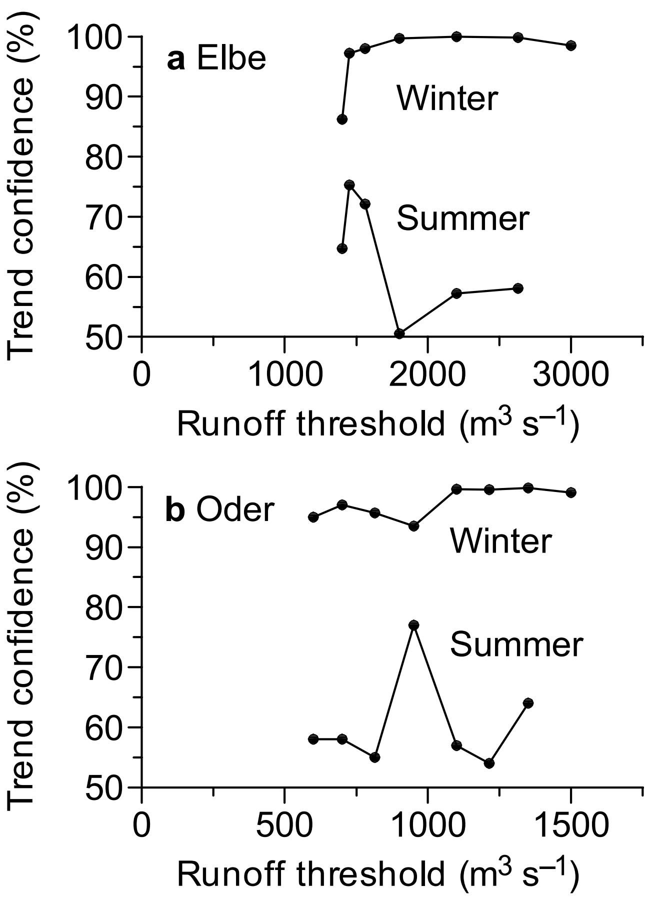

Figure 9. Confidence level of one-sided test (section 3.2.2.1) for trend in occurrence of extreme floods in dependence on the threshold in runoff (Figure 3) for the (a) Elbe and (b) Oder. Winter floods show downward trends, significant at the 90% and also higher levels; summer floods show downward trends that are not statistically significant.

climatic signal in the form of warming of that region [*Folland et al.*, 2001]. Elevated winter temperatures can reduce winter flood risk in two ways: first, via a reduced rate of strong river freezing and related ice jam, as was speculated previously [*Bronstert*, 1995; *Glaser*, 2001]; second, via a reduced rate of occurrence of a frozen soil, which has a low absorbing capacity [*Bronstert et al.*, 2000]. Unfortunately, homogeneous precipitation records for the middle Oder catchment area are not available for the nineteenth century, prohibiting a closer examination of causes of the apparent upward trend in summer flood risk of the Oder. Because the work of *Fischer* [1907], entitled (in translation) “The summer floods of the Oder from 1813 to 1903,” upon which the flood chronology of M03 strongly relies, gives a comprehensive view of various river locations over the century, it seems unlikely that the increase in Oder summer flood risk is an artifact resulting from data inhomogeneity across the boundary between documentary and instrumental data at 1850.

4.1.2. Instrumental Period

[78] The availability of continuous, daily runoff records for the Elbe (from 1852) and the Oder (from 1920) yields reliable trend estimates for the instrumental period. These trends are further tested using the method of *Cox and Lewis* [1966], which is described in section 3.2.2.1. In addition, the robustness of results is determined, that is, the degree of dependence on made assumptions.

[79] The occurrence rates (Figures 7 and 8) show decreases in winter flood risk (Elbe, Oder) and no significant changes in summer flood risk. This observation is confirmed by the statistical test, which yields one-sided confidence levels ($1 - P$) of 99.9% (Elbe, class 2–3), 98% (Elbe, class 1–3), 99.6% (Oder, class 2–3), and 96% (Oder, class 1–3) in the case of winter floods; and 58% (Elbe, class 2–3), 72% (Elbe, class 1–3), 54% (Oder, class 2–3), and 58% (Oder, class 1–3) in the case of summer floods.

[80] Applying the statistical test to daily runoff records from Elbe stations Děčín (1887–1990) and Barby (1887–1990) yielded roughly similar results, while applying it to the monthly record from Oder station Połęcko (1946–1987) gave no significant results owing to the shortness or lower data size of that record.

[81] To assess how robust test results are against the choice of magnitude class bounds (Figure 4), confidence levels were calculated for a range of class bounds. The results (Figure 9) show little such variation, attesting a high degree of robustness to trend test results.

[82] To evaluate whether uncertainties in the stage-runoff relation (Figure 4) are small enough not to corrupt trend test results, a simulation study was carried out. For both the Elbe station Dresden and the Oder station Eisenhüttenstadt, 2000 simulated runoff time series were generated by adding Gaussian noise up to twice the uncertainty ($2\sigma_r$, that means, a conservative approach) to the runoff time series. For each simulation, the trend test was repeated, yielding on average the same results as for the original data, making the trends robust in that respect.

[83] To inspect whether inhomogeneities in the records across the boundary documentary/instrumental data could have influenced the finding of downward trends in winter flood risk, a set of trend test experiments was performed. Therein, the start date of the analyzed time intervals was successively changed in 5-year steps from a few decades before the start of the instrumental period (Elbe, 1852; Oder, 1920) to a few decades after. These experiments revealed only minimal variations over time in the test P values for the heavy floods (class 2–3), thus attesting to the records' homogeneities. Some variations were found for the Oder when including also weak winter floods (class 1), which may indicate inhomogeneities.

[84] Attempts to identify short-term changes (last ~20–40 years) in flood risk gave only insignificant trends in the hypothesis test. This points to a dilemma: Focusing on the extremes (instead of the average) means that only minimal data are available. This makes it hard to obtain significant trends over short periods. This also indicates that for assessing future significant trends in flood risk as a result of the current “greenhouse experiment” on the basis of observations, a few decades of data recording may have to pass. Before that, it is wise not to speculate, as *Kundzewicz* [2004] did, about possible outcomes because such speculations lack the statistical basis.

[85] Sections 4.1.2.1–4.1.2.3 explore possible causes for the observed downward trends of winter flood risk in the

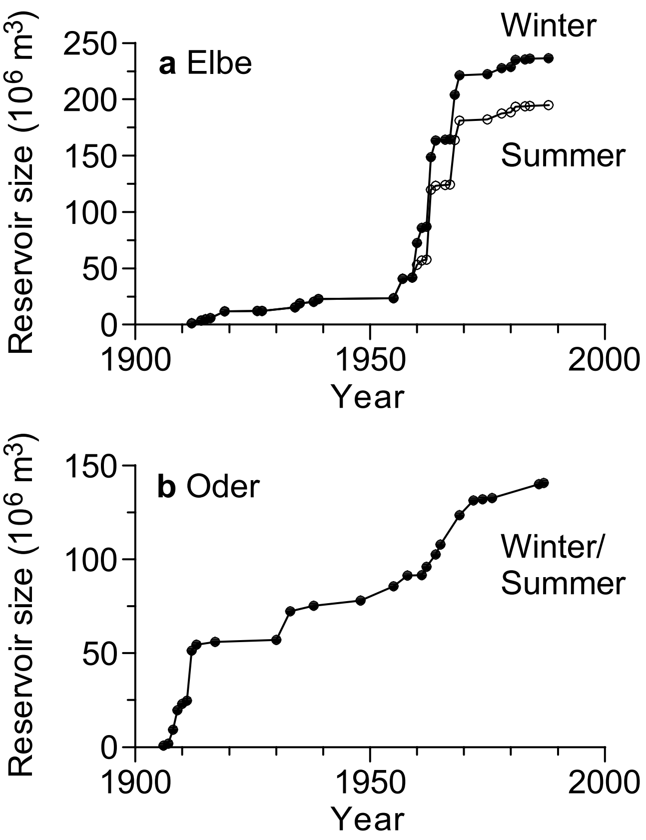

Figure 10. Total manageable reservoir size above (a) Elbe station Dresden and (b) Oder station Eisenhüttenstadt. Data are from *Bundesanstalt für Gewässerkunde* [2000] and *Grünewald et al.* [1998]. In the case of the Elbe, volumes for winter are larger than those for summer.

instrumental period and the absent trends for summer floods.

4.1.2.1. River Freezing

[86] We showed in previous sections that strong river freezing in winter and subsequent ice breakup and jam were common during the historical period (sections 2.1.1.1 and 2.2.1.1). M03 estimated that of 103 Elbe floods that allowed unambiguous distinction, 91 were connected with a frozen river; for the Oder the number is 28 out of 34 events. Contrasting these numbers with the proportions of ice floods in the twentieth century, that is, 2/11 for the Elbe (section 2.1.2.3) and 4/28 for the Oder (section 2.2.2.3), strongly suggests a climatic cause (regional warming). This climatic connection has been explained in section 4.1.1. M03 mentioned pollution of river waters by soluble matter (salt) as another explanation. However, given the order of typical salt concentrations in the rivers during the twentieth century (*Bergemann* [1995] notes a range of concentrations of $c = 40$ to 740 mg/l Cl^- for Elbe freshwater during 1926–1994), the reduction of the freezing point ($\Delta T \approx c \cdot 103.2$ K) is probably much too small.

4.1.2.2. Reservoir Construction

[87] Figure 10 shows the time-dependent volumes, $V(t)$, of all reservoirs above a station (Dresden, Eisenhüttenstadt), which can be employed for flood management. Significant volumes were reached only in the middle of the twentieth century.

[88] To evaluate whether the observed trends during the instrumental period were the effect of reservoir construction, M03 constructed flood records that correct for this effect. The aim was to find a flood record that would have resulted if reservoir size were constant at present level, V_p. To calculate reduced runoff, Q_r, for a flood that could have been obtained if $V(t)$ equaled V_p, M03 "cut off" the flood peaks in daily runoff, $Q(t)$:

$$\int [Q(t) - Q_r] dt = V_p - V(t), \tag{9}$$

where the integral is over the time a flood lasted. This was carried out for all floods (Dresden, Eisenhüttenstadt) in the instrumental period. Figure 11 illustrates reservoir correction in the case of the January 1920 Elbe flood at Dresden.

[89] The results (Table 2) show that in the case of class 2–3 floods, no changes in the sign and the confidence level of the trend could be induced by flood management of reservoirs. The reservoir size is too small for influencing the occurrence of heavy floods. When also including class 1 floods, a significant lowering of flood risk is theoretically possible. However, such a lowering assumes 100% utilization of the available reservoirs, which is practically impossible. This means that the theoretical reduction in flood size is an upper limit (Figure 11). The consequence is that the trend test applied to reservoir-size-corrected records becomes liberal (that is, it has a lower than nominal confidence level) as regards upward trends, and it becomes conservative (higher than nominal confidence level) as regards downward trends. Therefore the upward trend in reservoir-size-corrected Elbe summer floods (classes 1–3) is likely an artifact owing to an overcorrection. Although M03 alerted readers of this fact, *Bronstert et al.* [2004], who

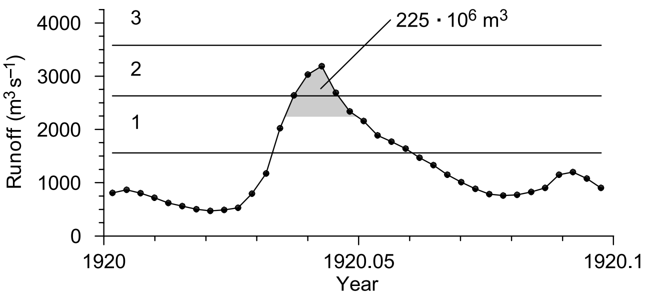

Figure 11. Construction of a flood record with assumed constant reservoir size at present level, in the case of the January 1920 winter flood of the Elbe at Dresden. Present manageable winter reservoir size is 237 × 10^6 m^3; in January 1920 it was 12 × 10^6 m^3 (Figure 10). Using hypothetically the full difference (225 × 10^6 m^3) to reduce the flood peak (integrated daily runoff, equation (9)) would make the January 1920 flood a class 1 event (instead of class 2). Using the full difference is equivalent to assuming 100% utilization of all reservoirs in tributaries above a station (including optimal reservoir management). Because, in practice, total reservoir size cannot be utilized to such a degree, the shown reduction (in runoff, that is, magnitude class) is an upper limit.

Table 2. Results of Trend Test (One-Sided 90% Confidence Level) of Null Hypothesis "Constant Flood Occurrence Rate," Instrumental Period[a]

	Trend	
	Uncorrected	Corrected
Elbe (1852–2002)		
Winter		
Class 2–3	down	down
Class 1–3	down	no
Summer		
Class 2–3	no	no
Class 1–3	no	up
Oder (1920–2002)		
Winter		
Class 2–3	down	down
Class 1–3	down	no
Summer		
Class 2–3	no	no
Class 1–3	no	no

[a] Reservoir size correction is described in Figure 11.

reported about the work of M03, unfortunately misrepresented this point.

4.1.2.3. Land Use Changes

[90] Collectivization of farmland in lower parts of the middle Elbe (below Dresden) and the lower Elbe since ~1950 changed agricultural land use in the German Democratic Republic. *van der Ploeg and Schweigert* [2001] analyzed the 10 heaviest floods (winter and summer combined) of the Elbe at Dresden and Wittenberge (lower Elbe) during the twentieth century and claimed, without giving a confidence level, that these land use changes had an increasing effect on flood risk in lower middle and lower Elbe regions. With the caveat that the main information on Elbe floods in the present paper comes from Dresden, this claim seems too strong, given (1) the shortness of the relevant period (~50 years) and the difficulty to obtain statistically significant results and (2) the test result (no upward trend) using the runoff time series from lower middle Elbe station Barby. Furthermore, floods in winter and summer should be analyzed separately because their hydrological properties are different.

[91] As for the early centuries of the millennium, little quantitative information is known about deforestation in the mountainous areas of the Elbe and Oder catchment areas during the beginning of the instrumental period. Since deforestation, if effective, would have led to an increase in flood risk (section 4.1.1), we assess from the absence of significant upward trends in flood risk (Table 2) that deforestation had negligible influence on flood occurrence during the instrumental period.

4.2. Correlation Fields: Floods Versus Atmospheric Pressure

[92] Figure 12 shows the point-wise biserial correlation coefficient between flood occurrence and atmospheric pressure indices at a spatial grid. The correlation maps indicate a significant (90% level) influence of atmospheric circulation on flood occurrence of the rivers Elbe and Oder during the interval 1658–1999. Taking into account that a "Großwetterlage" persists at maximum for 10–15 days in central Europe, it is remarkable that such an influence can be quantified using the coarsely resolved data. We assume that the considerable lengths of flood and pressure time series enabled detection.

[93] Higher correlations were found for winter than for summer floods, which reflects the large-scale dominance of rain-bearing atmospheric processes in winter. The correlation patterns (Figure 12) indicate that during winter, zonal westerly airflow correlated with Elbe and, in lesser extent, Oder floods. Summer floods, on the other hand, are connected with a different, meridional atmospheric mode that involves an increased flow of warm and potentially humid air from the northeastern Mediterranean to the north, possibly along the Zugstrasse Vb (Figure 1).

[94] Point-wise biserial correlations were also calculated between differences in SLP and flood occurrences over the

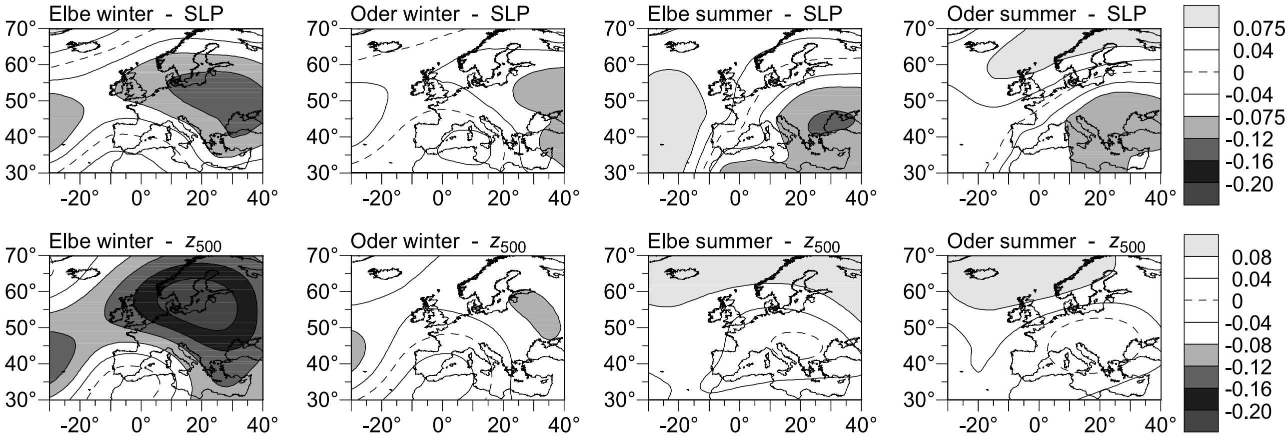

Figure 12. Contour maps of the point-wise biserial correlation coefficient between flood events (Elbe, Oder; winter, summer; classes 1–3) on the one hand and sea level pressure (SLP) or 500 hPa geopotential height (z_{500}) time series on the other; time interval, 1658–1999. Significant correlations (section 3.3) are on color scale. A negative (positive) correlation indicates a pressure below (above) the seasonal average at a geographic point during floods. Elbe and Oder catchment areas are located around 50°N, 15°E (Figure 2). See color version of this figure at back of this issue.

past ~350 years. The North Atlantic Oscillation (NAO) index (scaled SLP difference between Azores and Iceland), an indicator of the strength of westerly airflow to Europe [*Hurrell*, 1995; *Luterbacher et al.*, 1999], yielded no significant correlation with winter flood events of Elbe and Oder; similar results were obtained when using z_{500} instead of SLP. This shows that central European winter floods were not connected with warm, wet winters in western Europe (NAO index high). Other pressure indices involving one grid point in the area between 40° and 70°N and 15° and 25°E, like the EU1 index [*Luterbacher et al.*, 1999], however, yielded significant correlations with Elbe and Oder winter floods.

4.3. Role of the Zugstrasse Vb

[95] How important is a Zugstrasse Vb atmospheric pressure pattern for the occurrence of extreme summer floods? We find a significant, but weak correlation (Figure 12) between the meridional airflow in Vb situations and summer flood occurrence of Elbe and Oder over the past 350 years. *Fricke and Kaminski* [2002] suggest that the general weather type TrM, which includes a Vb situation, became more frequent over the past 120 years. This is an interesting point in that it is not global temperature changes that are invoked via the Clausius-Clapeyron equation (~7% more water in the atmosphere per 1 K increased temperature); a shift in the distribution of dominant weather situations in a certain region might be sufficient. However, our analyses for the Elbe and Oder region (section 4.1.2) show no trends in summer flood occurrence for that time interval. This discrepancy is likely the result of various sources of uncertainty: limited spatial and temporal resolution of flood and atmospheric pressure data (section 4.2; see also *Philipp and Jacobeit* [2003]) and also proxy error of the TrM weather type to indicate a Vb situation. As explained in section 1, besides a meridional airflow, several other requirements have to be met to produce Vb-related, strong rainfall. Unfortunately, the data situation as regards requirements such as cyclonic airflow, low convective lability, and prolonged flow against an extended orography makes it hard to perform a more detailed analysis of Zugstrasse-Vb-related rainfall in central Europe over the past centuries. We also note that *Fricke and Kaminski* [2002] provide no methodical details as to whether the claimed increase in TrM occurrence is significant.

5. Conclusions

[96] The time series of floods in central European rivers Elbe and Oder, constructed from C. Weikinn's documentary source texts and runoff measurements, are as follows: (1) regionally representative (middle Elbe, middle Oder), (2) continuous in time over the past nearly 1000 years, (3) at monthly time resolution, (4) seasonally (winter/summer) resolved, (5) (in the case of heavy floods, magnitude classes 2–3) in agreement with historically critically constructed documentary database CLIMDAT, which covers the interval 1500–1799, and (6) (in the case of heavy floods) homogeneous from 1500 to the present.

[97] The method of kernel occurrence rate estimation is currently unparalleled in its performance in estimating trends and their statistical significance in the occurrence of extreme events. This method (1) allows nonlinear and nonmonotonic trends; (2) imposes no parametric restrictions; and (3) provides bootstrap confidence bands, which are essential for evaluating whether observed trends are real or came by chance into the data. The method can be augmented by using the test of the null hypothesis "constant occurrence rate" in cases where the sign of the trend is of particular importance.

[98] We find for both the rivers Elbe and Oder (1) significant downward trends in winter flood risk during the twentieth century; (2) no significant trends in summer flood risk in the twentieth century; (3) significant variations in flood risk during past centuries, with notable differences between the Elbe and Oder. (Unfortunately, the trends for the twentieth century have been recently misrepresented as [*Diodato*, 2004, p. 393] "floods multi-day rainfall-induced . . . do not show a clear increase in central Europe.")

[99] The observed trends in flood risk: (1) are robust against uncertainties in the stage-runoff relations (instrumental period), (2) are robust against choice of runoff thresholds used to define a flood event (instrumental period), (3) show negligible influences of deforestation and agricultural land use changes (historical and instrumental periods), (4) (in the case of heavy floods) are insensitive to construction of reservoirs (instrumental period), (5) show minimal influences of other type of river engineering work such as length reductions (historical period), (6) show significant correlations with fields of atmospheric pressure variables, reinforcing the role of the cyclone's pathway Zugstrasse Vb, and (7) show coherent climatic signals in form of a reduced winter flood risk (fewer "ice floods") during the instrumental period as a response to regional warming.

[100] From our studies, we draw the following conclusions as regards flood protection and disaster management in central Europe. Although the handling of reservoirs cannot influence the occurrence of heavy floods, such a measure can be helpful to reduce the peak water stage. This was shown by *Bronstert* [2003] for the Elbe flood in August 2002, where the Havel detention basins were successfully employed. A second, more obvious measure to reduce the potential loss of life and economic damages is to reduce the amount of values or dangerous goods (oil, etc.) stored in flood-prone areas. Unfortunately, the opposite seems to have been done in Dresden, where the trade center "Elbepark," under water in August 2002, was considerably extended [*Grünewald et al.*, 2003]. A third measure comprises early warning services across national boundaries [*Becker and Grünewald*, 2003], for example, within the European Water Framework Directive of the (recently enlarged) European Union.

[101] From our studies, we envision the following situation for the mathematical modeling of flood risk in central Europe as a response to the future increase in greenhouse gas concentrations and a related likely warming. (See *Loaiciga et al.* [1996] for an extensive review on modeling flood risk in the Unites States.)

[102] The output from experiments with (1) an Atmosphere-Ocean General Circulation Model, forced using various greenhouse gas emission scenarios, is fed into (2) a regional climate model (RCM). Owing to the possible role of the Zugstrasse Vb and atmospheric pressure indices

for initiating rainfall and floods, the area presented in the RCM is ideally of size similar to that of the maps shown in Figure 12. The spatial resolution of the RCM is highest in the mountainous catchment areas of the studied rivers. (3) The RCM output forces a hydrological model (HM). The HM takes the following effects on flood risk into account: runoff modification in winter owing to a frozen soil, formation and breaking of river ice, reservoir management, dikes and other river engineering, and runoff modifications owing to land use changes. Dike breaking in particular is a challenging process to model.

[103] In our assessment, promising tools to achieve longer-term predictions of regional flood risk include the following models: LISLFLOOD [*Bates and De Roo*, 2000; *De Roo et al.*, 2001], RHINEFLOW [*Middelkoop et al.*, 2001], ECHAM4/OPYC3-HBV-D [*Menzel and Bürger*, 2002], and ELBA [*Merkel et al.*, 2002].

[104] We emphasize that our studies focused on the middle Elbe and middle Oder. It seems possible that other parts of these rivers, and also other rivers under low mountainous climate with the possibility of cold winters, exhibit similar trends (currently being analyzed). It might also be the case that rivers in more western parts of Europe show, unlike the Elbe and Oder, an influence of the NAO on the occurrence rate of extreme floods.

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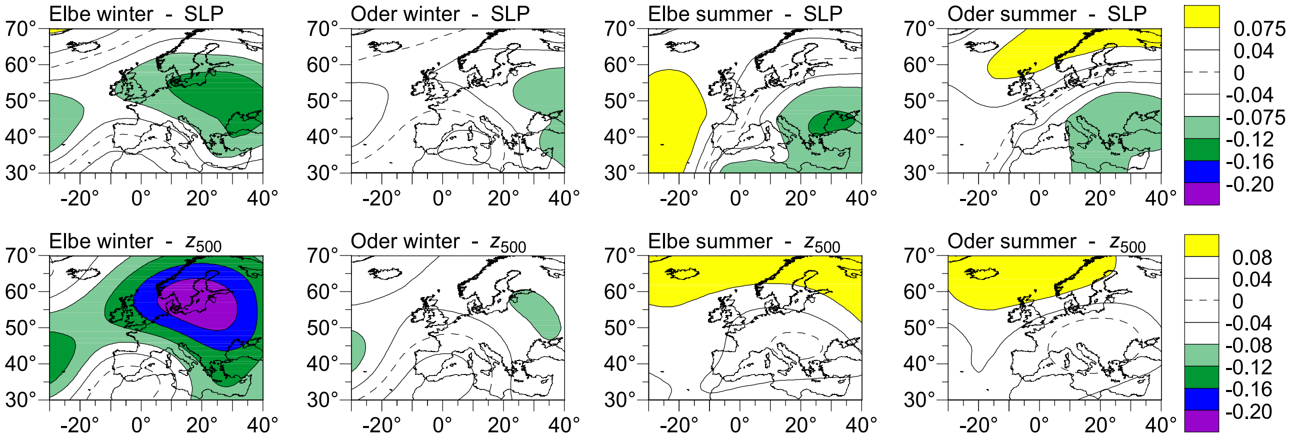

Figure 12. Contour maps of the point-wise biserial correlation coefficient between flood events (Elbe, Oder; winter, summer; classes 1–3) on the one hand and sea level pressure (SLP) or 500 hPa geopotential height (z_{500}) time series on the other; time interval, 1658–1999. Significant correlations (section 3.3) are on color scale. A negative (positive) correlation indicates a pressure below (above) the seasonal average at a geographic point during floods. Elbe and Oder catchment areas are located around 50°N, 15°E (Figure 2).